

Measurement Note

Measurement of failure in tough plastics at high strain rates

Summary

This Measurement Note details test methods used to characterise the failure of tough plastics at high strain rates. Such data are required for finite element simulations of impact situations. A new tensile specimen geometry, intended to provide a uniform strain region at high strains is described. High-speed photography and digital image correlation strain mapping have been used to accurately determine strain at failure.

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INTRODUCTION

Most engineering plastics are tough materials that can sustain large strains through yielding and plastic flow prior to failure. This makes them attractive materials for components that may have to sustain accidental impact loading. In such applications, finite element analysis can be used to assist with the design of a component to ensure that critical force and strain levels are not exceeded in an impact event. For these analyses, it is necessary to know under what conditions the material will fail by rupture and therefore will not be able to absorb additional energy. Even in the absence of a stress analysis, failure properties are needed for the purposes of materials selection and improvement.

The most basic information that will characterise failure behaviour is the stress and strain at failure, and how these quantities vary with strain rate and temperature. Of particular importance is the availability of these properties at high strain rates associated with impact events, and at temperatures below ambient, since these conditions are known to have a significant influence on toughness.

This Measurement Note is concerned with the measurement of the stress and strain in a tensile test specimen. The method is particularly appropriate for test speeds of 1 m/s or higher and is suitable for tests at different temperatures.

With tough plastics, failure usually takes place after extensive yielding and plastic flow. Under these conditions, the strain in a standard tensile specimen is not uniform. It is therefore necessary to use an alternative specimen geometry described in the next section. A description of the measurement of strain in this specimen using a video camera in high-speed tensile tests then follows. The determination of strain levels in the specimen using image correlation analysis is also described.

A NEW TENSILE SPECIMEN GEOMETRY

The standard specimen geometry

The ISO Standard for tensile testing of plastics, ISO 527-2 [1], specifies the use of a specimen with a parallel-sided central region that allows extensometers with a large gauge length to be used in order to give high precision in the measurement of strain. At strain levels associated with the peak in stress in a stress/strain curve, plastic flow starts to dominate the deformation and the strain distribution in the specimen becomes non-uniform. The ISO Standard then refers to the measurement of a nominal (or average) strain.

The extent of the strain localisation depends on the flow behaviour of the polymer. In extreme situations, the localisation is clearly visible as a neck, but even where necking is not observed, there will still be a significant variation in the strain distribution in the gauge region of the specimen. Under these conditions, conventional extensometry can only give an average strain that will depend on the chosen gauge length and the location of the extensometer on the specimen.

A specimen geometry for high strain measurements

In order to obtain more meaningful measurements of strain, and in particular of strain at failure, an alternative specimen geometry has been chosen that is illustrated in Figure 1. The waisted region is defined by a constant radius that locates the maximum stress, and hence the onset of flow, at the centre of the specimen. The dimensions shown enable the specimen to be machined from the centre of a standard ISO tensile specimen. Finite element analysis calculations have been carried out on this specimen geometry to reveal stress and strain distributions in the central

region. The material used for these calculations is a propylene-ethylene copolymer. The large-strain, non-linear deformation behaviour of this material was described by an elastic-plastic model with a hydrostatic stress-sensitive yield criterion (the linear Drucker-Prager model). The dependence of yield behaviour on strain rate (rate-dependent plasticity) was included in the analysis.

A finite element analysis has been carried out to simulate a test at a speed of 1 m/s. The calculated distributions of the axial components of stress and strain are presented in Figure 2 at a grip displacement of 4.5 mm. These show that there is a region of predominantly uniform stress and strain in the specimen centre and that the strain is essentially uniform over a length of around 3 to 5 mm. This gives an indication of the gauge length that should typically be used for strain measurements. These calculations are supported by measurements of the strain distribution under the same conditions by the computer

analysis of images of the specimen taken by high-speed photography during a test.

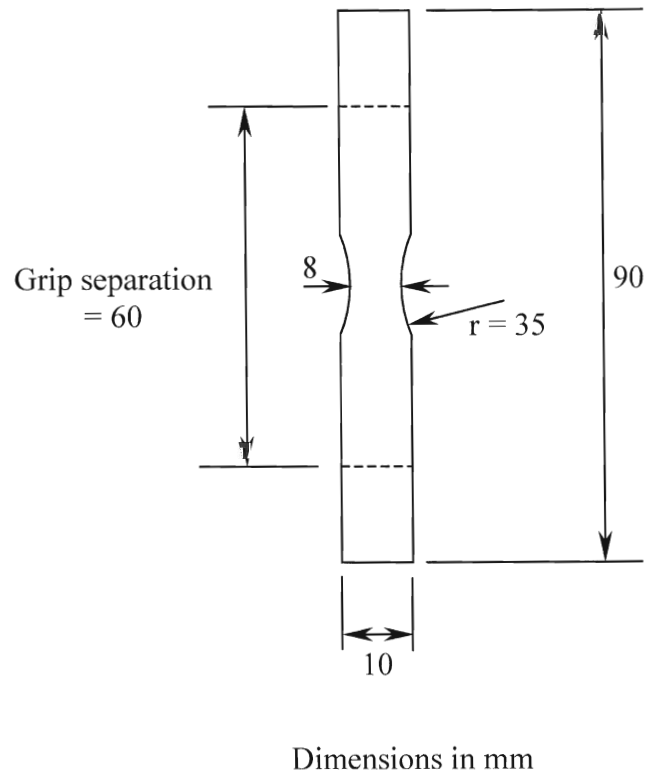


Figure 1 Geometry of new tensile specimen

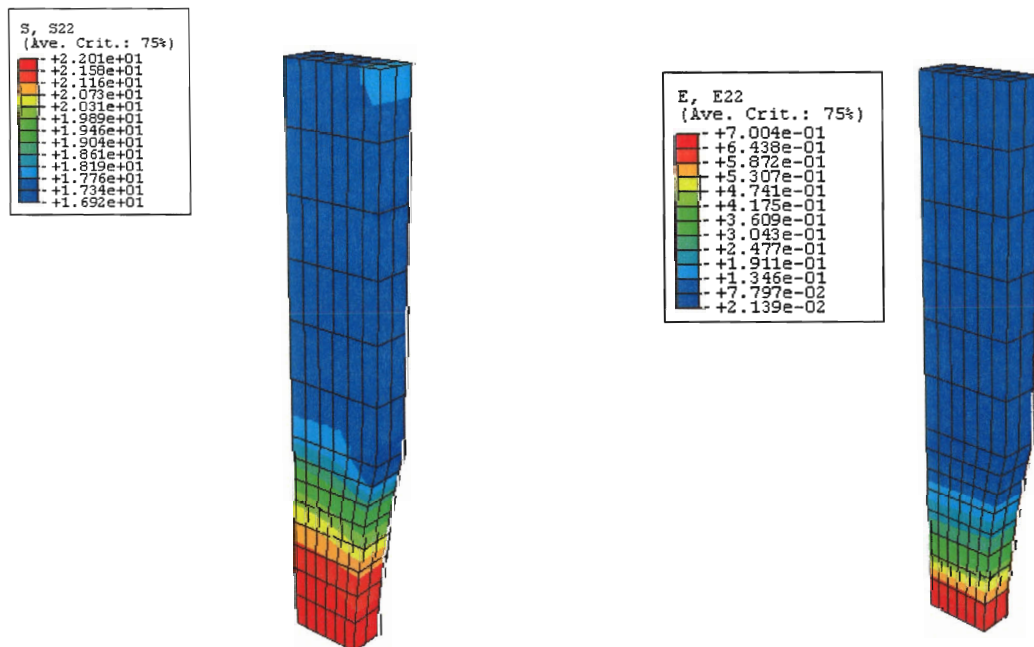


Figure 2 Distributions of axial components of true stress and engineering strain in specimen calculated by FE analysis (quarter of specimen shown due to symmetry)

HIGH SPEED TESTS

Apparatus

There are several issues that have to be considered when carrying out high-speed testing. Firstly, standard mechanical screw-driven test machines are not usually capable of achieving test speeds above 10 mm/s and so servo-hydraulic machines are normally used for these tests. At high speeds, errors in measurements of stress will generally arise because of resonances in the force transducer, in the test assembly and in the specimen. To minimise these, it is necessary to use components in the test assembly of low mass and high rigidity, and a high stiffness piezo-electric transducer with rapid response.

In addition, conventional contacting extensometers are unable to maintain contact in tests at high speed, and may introduce stress concentrations into the material via the knife edges.

The equipment used at NPL to measure stress and strain at high strain rates consists of an Instron 1343 servo-hydraulic test machine which is capable of actuator displacement speeds of up to 4 m/s. The test assembly consists of an aluminium actuator arm and small titanium manually

tightened grips. A Kistler 9041 piezo-electric load cell located within the test assembly is used to measure the load during the test. The displacement and load outputs from the machine during the test are recorded as voltages on a digital storage oscilloscope, and converted to actual values afterwards using a spreadsheet package.

The measurement of strains at high speeds can be achieved by using a digital high-speed video camera to photograph a series of images of the specimen during testing. The images are stored and are used after the test is complete to determine strain levels by computerised image analysis. For the tests illustrated in this Measurement Note a speed of 3000 frames per second was selected, with a shutter speed of 1/6000 of a second.

Specimens of the new tensile specimen geometry were machined from moulded standard tensile specimens, and the width and thickness at the centre of the specimen measured. In order to facilitate the computer analysis, the specimens were then carefully sprayed with paint to produce a random distribution of fine dots or "speckle pattern" on the surface (see Figure 3). The specimens were then placed within the grips, leaving a grip separation of 60 mm.



Figure 3 Specimen sprayed with speckle pattern

When the specimens have been positioned ready for testing, the camera is started to capture the images from the test. With the camera recording, the specimen is then tested in tension to failure at a cross-head displacement speed of 1 m/s.

An example of the force measurement against time to failure for one of the specimens is shown in Figure 4. The gradual rise at the beginning is due to the acceleration of the actuator at the start of the test. The point symbols on the curve signify when images of the specimen were taken with the high-speed camera – twenty images were taken from the start of the test to specimen failure.

Determination of strains by image analysis

The pictures were then processed using a digital image correlation (DIC) system

supplied by LaVision. This divides the initial image of the specimen into square elements whose size can be selected by the user. The software then correlates the movement of each element during the test to determine displacement vectors. Axial and transverse strain distributions can then be derived from the deformation maps.

Figure 5 shows the axial strain distribution in the specimen in the test shown in Figure 4, derived from the final image before failure. The grip displacement at this point was 4.5 mm. The measurements confirm the high strain localisation in the specimen and give a value for the engineering tensile strain at failure in the range 60-70 %. The strain rate in the test at failure was 190 s^{-1} .

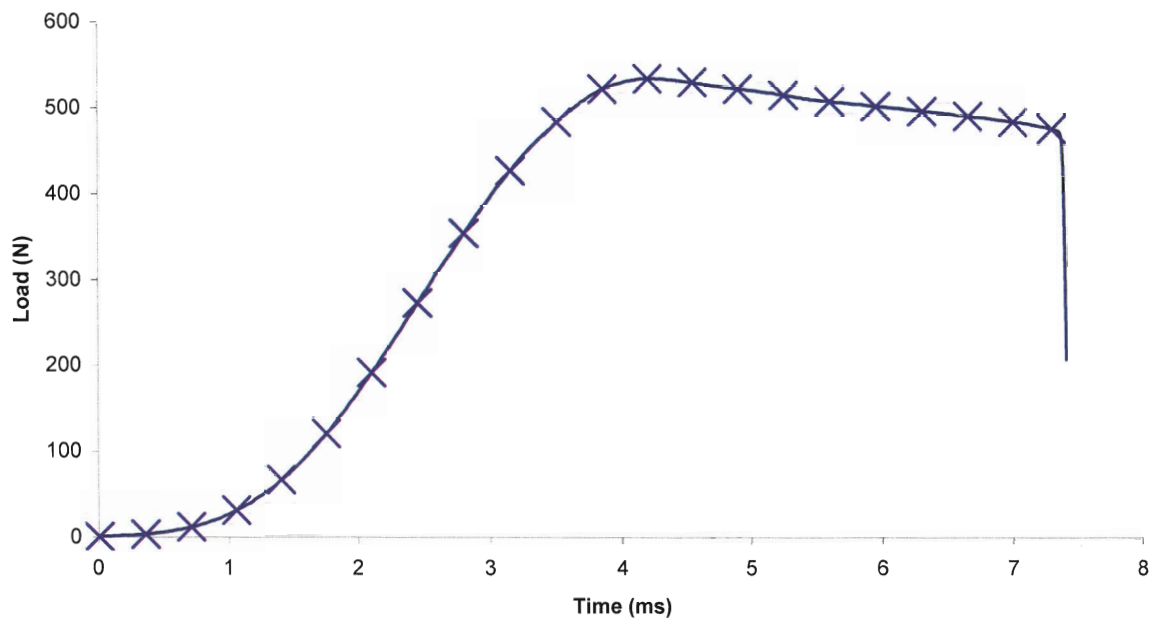


Figure 4 Load versus time plot of tensile test on new specimen tested at 1 m/s – points indicate when images were taken

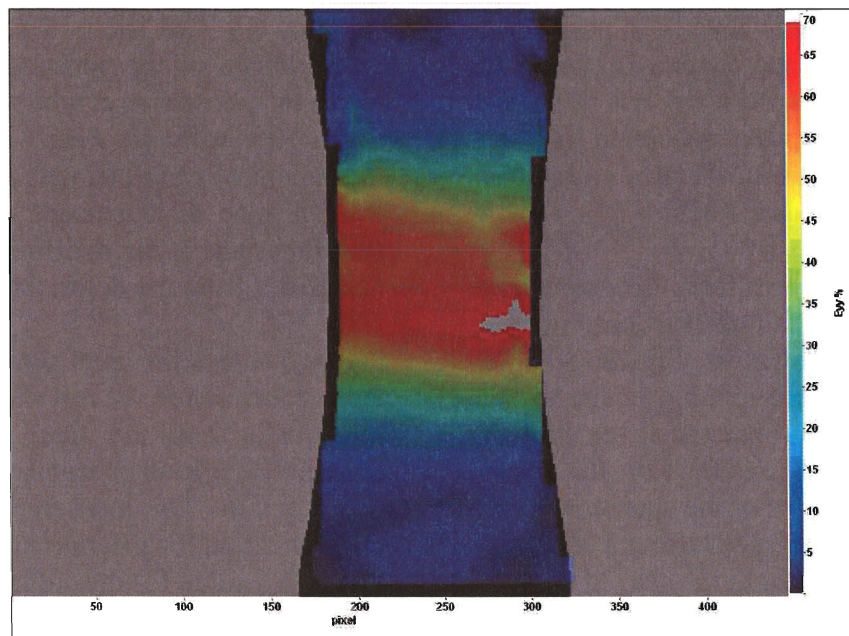


Figure 5 Axial strain distribution in the new tensile specimen just before failure

To determine a more precise measurement of strain in the centre of the specimen, the software is able to calculate the mean strain and the standard deviation using the elements within a rectangular area defined by the user. For the determination of strains in this test, an area 6 mm wide and 3 mm high in the centre of the specimen was chosen. The mean axial and transverse strains within this area were determined

for each image taken during the test. Using the lateral strain measurements from each image, true stresses can be derived. A plot of true stress against engineering strain is shown in Figure 6. This shows that the specimen failed at a strain of approximately 0.7, which is consistent with the result of the FE strain analysis at a grip displacement of 4.5 mm, shown in Figure 2.

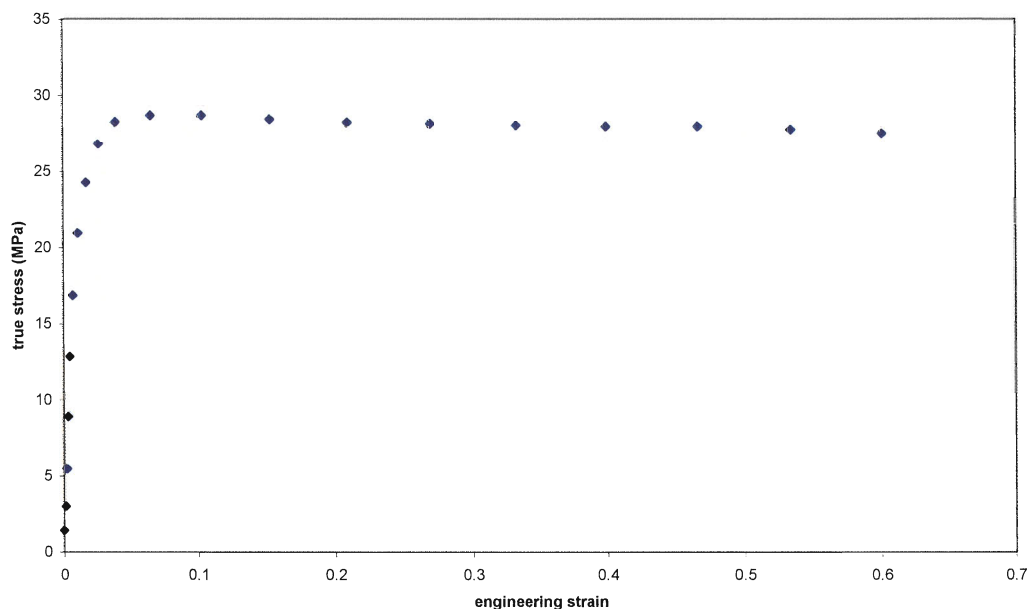


Figure 6 Derived true stress versus strain plot

Tests at low temperatures

Measurements can also be made at temperatures below room temperature, to investigate the effect of temperature on the properties. This can be achieved by mounting an environmental chamber on the test machine and enclosing both sets of grips and the specimen within it via portholes in the top and bottom of the chamber.

Some illustrative data showing the engineering stress versus the grip displacement is shown in Figure 7. It can be seen from the plots that lowering the temperature causes both the stiffness

(modulus) and the peak stress to increase, but reduces the strain to failure.

An estimate of the strain at failure at each of the two lower temperatures has been made by correlating the displacements at failure from Figure 7 with the closest point on the load-time curve in Figure 4, and then matching it to the corresponding point on the derived true stress-strain curve in Figure 6. The results are shown in Table 1. These strains are only estimates as in practice the results will be affected by the changes in flow pattern due to the varying temperatures.

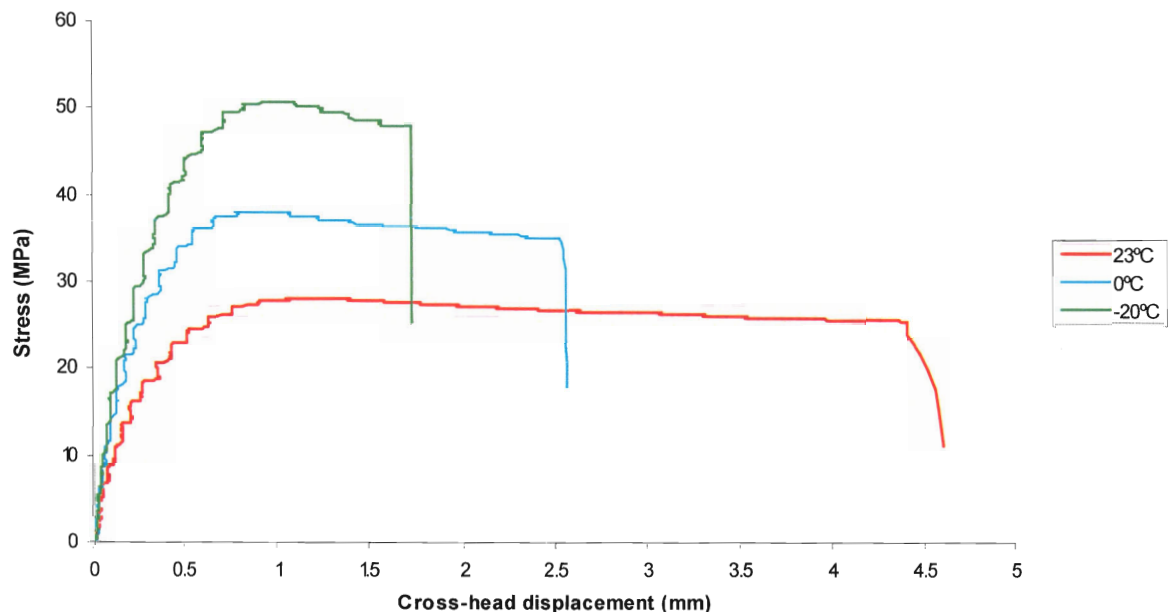


Figure 7 Effect of temperature on the tensile behaviour of specimen

Temperature (°C)	Estimated strain at failure
23	0.70
0	0.27
-20	0.15

Table 1 Estimated strain at failure for different test temperatures

CONCLUDING REMARKS

This Measurement Note has described a new specimen geometry for tensile tests that can be used for more accurate measurements of properties at high strains than is possible in standard specimen geometries. By carrying out tensile tests with the new specimen geometry and using a high-speed camera to analyse the images of the tests, the strain in tough plastic materials up to failure can be measured with high precision.

REFERENCES

- [1] BS EN ISO 527-2: 1996, *Plastics – Determination of tensile properties – Part 2. Test conditions for moulding and extrusion plastics*

ACKNOWLEDGEMENTS

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